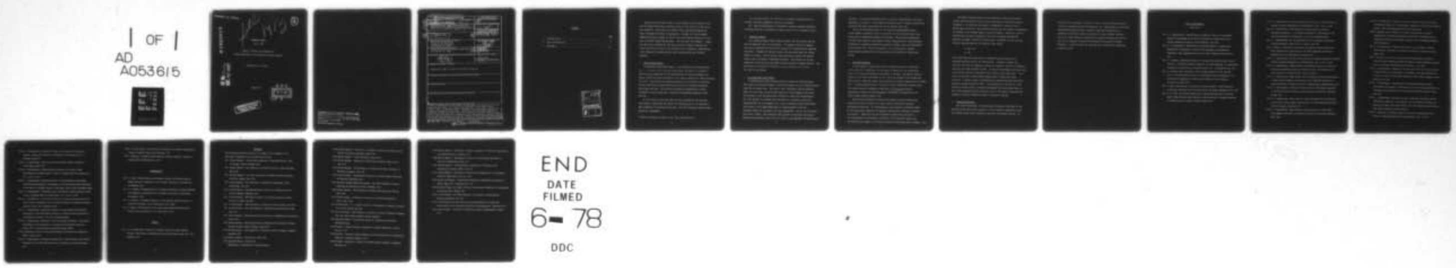
AD-A053 615 CALIFORNIA UNIV LOS ANGELES DEPT OF SYSTEM SCIENCE F/G 17/2
THEORY OF CONTROL AND COMMUNICATION SYSTEMS APPLICABLE TO THE D--ETC(U)
MAR 77 A V BALAKRISHNAN AFOSR-73-2492

UNCLASSIFIED AFOSR-TR-78-0846 NL

| OF |
AD
A053615



END
DATE
FILMED
6-78
DDC

See 1473

2

TECHNICAL REPORT

1973 - 1977

Theory of Control and Communication Systems Applicable to the Design of Aerospace Systems

AFOSR Grant No. 73-2492

March 1977

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFOSR-TR-78-0846
2. GOVT ACCESSION NO.: and
3. RECIPIENT'S CATALOG NUMBER: 9
4. TITLE (and Subtitle): THEORY OF CONTROL & COMMUNICATION SYSTEMS APPLICABLE TO THE DESIGN OF AEROSPACE SYSTEMS.
5. TYPE OF REPORT & PERIOD COVERED: Final rept.
6. PERFORMING ORG. REPORT NUMBER: 1973-1977
7. AUTHOR(s): A. V. Balakrishnan
8. CONTRACT OR GRANT NUMBER(s): AFOSR-73-2492
9. PERFORMING ORGANIZATION NAME AND ADDRESS: University of California, System Science Department, Los Angeles, CA 90024
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61102F 2304/A1
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Office of Scientific Research/NM, Bolling AFB, DC 20332
12. REPORT DATE: March 1977
13. NUMBER OF PAGES: 13
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): 16p.
15. SECURITY CLASS. (of this report): UNCLASSIFIED
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)
18. SUPPLEMENTARY NOTES
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Thirty six publications, four theses, and one report were published during the period of this grant. The research was conducted in the areas of system identification, stochastic control, nonlinear white noise theory, distributed systems, and computing algorithms. Perhaps the item of maximum immediate practical interest to the Air Force is in the area of Aircraft Flight Testing where flight test data from a Lockheed Jet Star was processed to extract stability and control derivatives as well as the intensity of the turbulence, demonstrating a new technique for handling flight data containing large gust response components.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

405 213

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

CONTENTS

During the period under review, a broad program of basic research in the area of Communication-Control Systems relevant to the needs of the Air Force was undertaken. Listed below are items in which significant progress was made, including both theory and application. Perhaps the item of maximum immediate practical interest to the Air Force worth special mention is in the area of Aircraft Flight Testing where -- for the first time anywhere -- flight test data from a Lockheed Jet Star was processed to extract stability and control derivatives as well as the intensity of the turbulence, demonstrating a new technique for handling flight data containing large gust response component.

1. System Identification

The Non-Linear White Noise Theory -- the likelihood ratio formula based on it -- developed by the Principal Investigator, was applied to generate a methodology and algorithms for the identification of unknown parameters of a dynamic system from noisy observation of its output, allowing for load disturbance [2,6,27]†. The formula was immediately applied to the problem of extracting aircraft stability and control derivatives as well as turbulence parameters from flight test data. The software developed was demonstrated on actual (Lockheed Jet Star) flight data. Among the distinguishing features of this work are:

i) The time-continuous data model is used as opposed to the discrete-time models; in particular this avoids the limitation due to the universally made assumption in the discrete-time models that the observation (sensor) noise samples are independent.

† Numbers in brackets are keyed to the 'List of Publications'.

ii) Aircraft response to turbulence is determined simultaneously with relevant turbulence parameters, such as its intensity.

iii) Improved determination of "secondary" aircraft parameters [hitherto considered difficult to estimate] by taking account of the "turbulence" input.

2. Stochastic Control

In a realistic flight control system one must take into account the fact that the hydraulic servo is rate-limited. In stochastic theoretic language this can be translated to mean that the control has a probability-one amplitude constraint. Although the system is linear, this constraint makes the overall problem non-linear. One of the most asked questions is whether the optimal control obeys a stochastic 'bang-bang' principle. This problem has now been completely solved [12,22] using rather advanced stochastic integral theories. New approximation techniques for stochastic control problems have also been developed in the process.

3. Non-Linear White Noise Theory

In extending the linear filtering theory of Kalman with time-continuous data models to non-linear systems, it has been customary to use a "Wiener Process" model for the sensor noise. Not only is this inconsistent with the physical model, but even worse, the non-linear operations ("Ito integral") that result (for instance in the likelihood ratio formula) are simply not instrumentable. The first attempt to circumvent this difficulty was to develop a theory of "approximating" the Ito integrals [11]. Later a systematic theory which models 'white-noise' in the engineering sense of "large-bandwidth" noise has developed [29,30,31], and shown to be more appropriate. This is the 'non-linear white noise' theory. This theory has been applied to filtering, control and Identification problems [9,17,18,23]. It leads to new algorithms in Identification

problems. In non-linear filtering theory it leads to 'implementable' non-linear operations on the data. It also opens up the whole area of stochastic differential equations with white noise rather than Wiener process input [16].

One of the water-shed results in the Wiener process-Martingale theory is the formula of Girsanov, and it is essential for the non-linear white noise theory that an appropriate analogue be developed. This has been accomplished: 'a white noise version of the Girsanov formula' was presented at the prestigious Conference on stochastic differential equations in Kyoto, under the chairmanship of Ito himself [19]. With this breakthru, it is now possible to examine identification problems for non-linear systems in the realistic 'white-noise' set-up.

4. Distributed Systems

In the problem of identifying aircraft stability and control derivatives in the presence of turbulence it is necessary to account for the non-rational nature of the turbulence spectrum [Von Karman vs. Dryden]. The dynamic system is lumped, but the state noise model is not. Hence the standard finite dimensional theory does not apply any longer, and constructing 'rational' approximation is cumbersome. A direct method in which a 'canonical' partial differential equation model for linear systems is developed is described in [1,23] and preliminary computational studies have been initiated. This theory is applicable to all linear systems whether lumped or not.

Identification problems for distributed parameter systems involve novel features which have no parallel in lumped systems (described by ordinary differential equations). An understanding of such problems is essential before we can develop the capability for applying identification techniques to handle such systems. Among these are the complexities introduced by the need to include phenomena on the boundary in addition to the (interior) region, and the modelling for example of stochastic processes incorporating space variables [24].

The Kalman filtering theory has been extended to distributed parameter systems (with distributed control and/or observation) by Functional Analysis Techniques -- in particular the theory of semigroups of operators over a Hilbert Space [9,13,25]. The problems that arise when the control or observation is confined to the boundary appear to be quite complex. Indeed this class of problems does not have an analogue in the case of ordinary differential equations and makes "intuition" difficult also. Basically it turns out that we have a generalization of the familiar linear system

$$\dot{x} = Ax + Bu$$
$$y = Cx$$

to the case where the state-space is a Hilbert Space and A,B,C are all unbounded operators and B,C are "uncloseable". A theory to handle this situation for analytic semigroups (arising for example in the case of diffusion equations) has been developed [25,34]. A study of the boundary noise-input case for parabolic systems is presented in [14], using a white noise model. It is shown that the white noise concept extends easily to space-time random processes. A general theory of Identification problems involving distributed parameter systems is given in [10]. A new application of the theory to the problem of active control in unsteady aerodynamics (with potential impact on the flutter problem) has been initiated in [37]. The related stabilizability problems in infinite dimensional spaces is treated in [35,38].

5. Computing Algorithms

The 'epsilon-technique' of the Principla Investigator (developed in the previous period 1968-72) has continued to be an effective computational tool for solving optimal control problems, especially time-optimal control. An

extension of the technique to handle the case of state constraints-equality as well as inequality has been developed in [3]. Application to a non-linear time-optimal problem arising in Aircraft Flight Path Optimization is presented in [15] with a view in particular to obtain feedback solutions. One of the 'side' benefits accruing from the epsilon-technique has been the fact that it provides a constructive technique for proving the Maximum Principle -- a proof of this kind removing some of the earlier limitations is given in [26].

LIST OF PUBLICATIONS

1973- 1977

[1] A. V. Balakrishnan, "Identification and Adaptive Control of Non-Dynamic Systems", Proceedings of the 3rd IFAC Symposium on Identification and Process Parameter Estimation, The Netherlands, June 1973

[2] A. V. Balakrishnan, "Identification of Systems Subject to Random State Disturbance", Proceedings of the 5th IFIP Conference on Optimization Techniques, Rome, Springer-Verlag Lecture Notes, Computer Science Series, 1973

[3] J. W. Mersky, "A Maximum Principle for General Constrained Optimal Control Problems: An Epsilon Technique Approach", 5th IFIP Conference on Optimization Techniques, Lecture Notes in Computer Science Vol. 3, Springer-Verlag, 1973

[4] R. Glowinski and M. Bristeau, "Finite Element Analysis of the Unsteady Flow of a Viscous-Plastic Fluid in a Cylindrical Pipe", Proceedings of the International Symposium on Finite Element Methods in Flow Problems, Hunstville, Alabama 1973

[5] G. Koch, "Some Results on Stochastic Bilinear Systems", Fourth Symposium on Nonlinear Estimation and Its Applications, San Diego, September 10-12, 1973

[6] K. W. Iliff, "An Aircraft Application of System Identification with State Noise", NATO Advanced Study Institute on New Directions in Signal Processing in Communication and Control, England, August 1974

[7] A. V. Balakrishnan, "Stochastic Optimization Theory in a Hilbert Space I", Journal of Applied Mathematics and Optimization, Vol. 1, No. 2, 1974

[8] A. V. Balakrishnan, "Identification-Inverse Problems for Partial Differential Equations - a Stochastic Formulation", Proceedings of the 6th IFIP Conference on Optimization, July 1974, Springer-Verlag

[9] A. V. Balakrishnan, "On the Approximation of Ito Integrals Using Band-Limited Processes", SIAM Journal on Control, May 1974

[10] J. Ruzicka, "A Stochastic Continuous Time Optimal Control Problem with Noisy Observations", Proceedings of the Fifth Symposium on Nonlinear Estimation and its Applications, September 1974

[11] A. V. Balakrishnan, "A Note on the Structure of Optimal Stochastic Controls", Journal of Applied Mathematics and Optimization, Vol. 1, No. 1, 1974

[12] A. V. Balakrishnan, "Identification and Stochastic Control of a Class of Distributed Parameter Systems with Boundary Noise", Proceedings of the IRIA Conference on Control Theory, Paris, June 1974

[13] A. V. Balakrishnan, "Time-Optimal Control Synthesis for Non-linear Systems: A Flight Dynamic Example", Proceedings of the IRIA-IFIP Conference on Computing Methods in Applied Sciences and Engineering, Springer-Verlag 1974

[14] A. V. Balakrishnan, 'Stochastic Bilinear Partial Differential Equations' in "Variable Structure Systems", edited by Mohler and Ruberti, Springer-Verlag, 1974

[15] A. V. Balakrishnan, "White Noise Vs. Wiener Process Models in Filtering and Control", invited paper, Proceedings of the IFAC Symposium Stochastic Control, Budapest, September 1974

[16] A. V. Balakrishnan, "White Noise Vs. Wiener Process", invited paper, Johns Hopkins Conference on Information Sciences and Systems, Baltimore, April 1975

[17] A. V. Balakrishnan, "Stochastic Control of Systems Governed by Partial Differential Equations", invited paper, Symposium on Multivariate Analysis, Dayton, 1975, Proceedings published by North-Holland

[18] H. Watanabe and M. Hitsuda, "On a Causal and Causally Invertible Representation of Equivalent Guassian Processes", Proceedings of the Symposium on Multivariate Analysis, Dayton, 1975, Proceedings published by North-Holland

[19] A. V. Balakrishnan, "A White Noise Version of the Girsanov Formula" invited paper, Conference on Stochastic Differential Equations, Kyoto, Japan, 1975

[20] J. Ruzicka, "On a Class of Stochastic Bang-Bang Control Problems", Control Theory, Numerical Methods and Computer Systems Modelling, Lecture Notes in Economics and Mathematical Systems No. 107, 1975

[21] A. V. Balakrishnan, 'Stochastic Filtering and Control of Linear Systems" A General Theory', Invited Paper, Proceedings of the ONR Conference on "Control of Partial Differential Equations", Naval Surface Weapons Center, Maryland, May 1976

[22] A. V. Balakrishnan, 'Identification Distributed Parameter Systems Non-Computational Aspects', Proceedings of the IFIP working conference on 'Modelling and Identification of Distributed Parameter Systems', Rome, June 1976

[23] A. V. Balakrishnan, 'Stochastic Control of Systems Governed by Partial Differential Equations', Proceedings of the 2nd Kingston Conference on Differential Games and Control Theory, June 1976, Kingston, Rhode Island, Proceedings published by Marcel Dekker

[24] L. D. Berkovitz, "A Penalty Function Proof of the Maximum Principle" Journal of Applied Mathematics and Optimization, Vol. 2, 1976

[25] A. V. Balakrishnan, "Parameter Estimation in Stochastic Differential Systems: Theory and Practice", in Advances in Statistics, Vol. 5, Academic Press 1977

[26] A. V. Balakrishnan, "Are all Non-Linear Systems (nearly) Bilinear?", inited paper, JACC, 1977

[27] A. V. Balakrishnan, "Radon-Nikodym Derivatives of a Class of Weak Distributions on Hilbert-Spaces" Journal of Applied Math and Optimization. Vol. 3, No. 3, 1977

[28] A. V. Balakrishnan, "Likelihood Ratios for Time-Continuous Data Models: The White Noise Approach", Proceedings of the IRIA International Conference on New Trends in Systems Analysis, Versailles, France, 1976, Springer-Verlag

[29] A. V. Balakrishnan, "Likelihood Ratios for Signals in White Gaussian Noise" Journal of Applied Math and Optimization, Vol. 3, No. 4, 1977

[30] A. V. Balakrishnan, "On Quickest Detection of System Structure Variation", Invited Paper, Proceedings of the US-Italy Conference on Variable Structure Systems, Sicily, 1977, Springer-Verlag

[31] A. V. Balakrishnan, "Likelihood Rations for Gauss-Measure Noise Models" Proceedings of the Oberwolfach Conference on "Measure Theory Applications to Stochastic Analysis", July 1977, Springer-Verlag

[32] A. V. Balakrishnan, "Boundary Control of Parabolic Equations: LQR Theory" Proceedings of the Conference on the Theory of Non-Lineary Operators, Berlin, 1977, to be published by Akademie-Verlag, Berlin

[33] C. Benchimol, "A Note on Weak Stabilizability of Contraction Semigroups" SIAM J. Control 1977

[34] A. V. Balakrishnan, "Stochastic Optimization: Time Continuous Data Models" Proceedings of the 8th IFIP Conference on Optimization, Springer-Verlag, 1977

[35] A. V. Balakrishnan, 'Active Control of Airfoils in Unsteady Aerodynamics', Journal of Applied Math and Optimization, 1977

[36] C. Benchimol, 'Feedback Stabilizability in Hilbert Spaces', Journal of Applied Math and Optimization, 1977

DISSERTATIONS

[1] K. Iliff, "Identification and Stochastic Control with Applications to Flight Control in Turbulence", Ph.D. Thesis, University of California, Los Angeles, 1973

[2] J. W. Mersky, "An Application of the Epsilon Technique to Control Problems with Inequality Constraints", Ph.D. Thesis, University of California, Los Angeles, 1973

[3] D. Washburn, "A Semigroup Approach to Time Optimal Boundary Control of Diffussion Processes, Ph.D. Dissertation, 1974, UCLA

[4] A. Bagchi, "Identification of Continuous Time Dynamical Systems with Unknown Noise Covariance", Ph.D. Dissertation, 1974

REPORTS

[1] A. V. Balakrishnan, "A Theory of Adaptive Control of Linear Dynamic Systems", UCLA School of Engineering and Applied Science, Report No. 7372, September 1973

BIOGRAPHY

The following additional material to be added to the biography of the principal investigator for the period under review.

[1] Invited Speaker: International Symposium on Computing Methods, IRIA, Le Chesnay, France, December 1973

[2] Invited Speaker: NSF Conference on Stochastic Control, North Carolina, April 1974

[3] Invited Speaker: U.S.-Italy Conference on Variable Structure Systems, Corvallis, Oregon, June 1974

[4] Invited Speaker: 6th Conference on Optimization Techniques, IFIP, Novosibirsk, July 1974

[5] Invited Speaker: NATO Advanced Study Institute on Communication and Control, England, September 1974

[6] Invited Speaker: NSF-Italy Conference on Variable Structure Systems, Corvallis, Oregon, May 1974

[7] Invited Speaker: IRIA Conference on Stochastic Control, Paris, June 1974

[8] Invited Speaker: 6th IFIP Symposium on Optimization, Novosibirsk, USSR, July 1974

[9] Invited Speaker: NATO Advanced Study Institute on Communication and Control, August 1974

[10] Invited Speaker: Working Conference on Modelling and Simulation of Water Resource Systems, Ghent, Belgium, August 1974

[11] Invited Speaker: IFAC Symposium on Stochastic Control, Budapest, Hungary, September 1974

[12] Seminar Speaker: IBM San Jose, March 1975

[13] Appointed Editor: Book Series Applications of Mathematics, Springer-Verlag

[14] Invited Speaker: Conference on Information Sciences and Systems, Johns Hopkins University, Baltimore, April 1975

[15] Seminar Speaker: Purdue University, April 1975

[16] Invited Speaker: Symposium on Multivariate Analysis, Dayton, Ohio, June 1975

[17] Invited Speaker: NSF Conference on Stochastic Systems, University of Kentucky, Lexington, June 1975

[18] Invited Speaker: International Conference on System Theory, University of Minnesota, September 1975

[19] Technical Program Committee Chairman: 6th IFIP Conference on System Modelling and Optimization, Nice, September 1975

[20] Invited Speaker: IFAC Conference on System Identifications, Tbilisi, USSR, 1976

[21] Invited Speaker: Conference on Stochastic Differential Equations, Kyoto, Japan, 1976

[22] Invited Guest: B. A. Steklov Institute of Mathematics, Academy of Sciences of the USSR, Moscow, May 1976

[23] Invited Speaker: ONR Conference on Control of Partial Differential Equatio May 1976, Naval Surface Weapons Center, Maryland

[24] Appointed Editor: Lecture Notes Series in Information and Control, Springer-Verlag

[25] Chairman: Program Committee, Symposium on Applied Mathematics, Vienna, Austria, 1977

[26] Chairman: Technical Program Committee, 8th IFIP Conference on Optimization Techniques, Wurzburg, Germany, 1977

[27] Chairman: Workshop on 'Control of Flexible Flight Vehicles' Los Angeles, February 1977

[28] Seminar Speaker: University of Oregon, Department of Electrical Engineering and Computer Science, February 1977

[29] Seminar Speaker: Massachusetts Institute of Technology, Department of Electrical Engineering, March 1977

[30] Invited Speaker: 2nd International Conference on "Statistics and Probability", Vilnius, USSR, June 1977

[31] Invited Speaker: Conference on "Measure Theory-Applications to Stochastic Analysis" Oberwolfach, July 3-9, 1977

[32] Invited Participant: International Workshop on Probability and Analysis: Kyoto, Augut 1977. Organized by K. Ito

[33] Received "Silver Core Award" from the International Federation for Information Processing (IFIP), August 1977

[34] Invited Speaker: 8th IFIP Conference on Techniques of Optimization, Wurzburg, September 6-9, 1977

[35] Visited Edwards Air Force Base and discussed problems of Flight Path Reconstruction with the Dynamic Modelling Technology Group - September 1977

[36] Seminar Speaker: University of Minnesota, School of Mathematics, October 1977